



The Particle Size of Mixture of Powders

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The Particle Size of Mixture of Powders

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清水 清 : 混合粉体の粒径について

§ 1. Introduction

For the physical studies of powder in the sieve or subsieve range, we are required to find a size-distribution of particles. Now, it seems that the size frequency of powder is measured precisely if it is over and over again measured with high accurate technique and the data are treated statistically. But when we are required to consider irregular particles as like as practical powder, our problem becomes difficult as there are many noteworthy facts. Indeed, no known method is available for defining an irregular particle in geometric terms. We cannot assign its length, breadth, and thickness in a manner permitting accurate determination of volume or surface, as in the case of regular parallelopiped. In the case of mixing powder of different specific surface, these problems become still more difficult. In our study, a correlation between the specific volume surface of mixed powder determined by the permeability method and the mixtity of practical powder was experimentally considered.

§ 2. Development of Theory

Specific surface area : The determination of accurate surface area to volume ratio is of primary importance if the Kozeny-Carman constant is to be determined from measurements of permeability and porosity by the application of the basic Kozeny-Carman Equation⁽¹⁾

$$K = \frac{\varepsilon^3}{kS_0^2(1-\varepsilon)^2} \quad (1)$$

where k is the Kozeny-Carman constant, K permeability, ε porosity, and S_0 surface area per unit volume of solid particles in aggregate. For convenience and because of its familiarity, the term "Kozeny-Carman constant" is used throughout this work for the quantity, k . Actually, k is a parameter and the anomaly of a porosity-dependent "constant" will be encountered. Then from Equation (1), the specific surface area of powder is expressed by the Equation

$$S_0 = \sqrt{\frac{\varepsilon^3}{Kk(1-\varepsilon)^2}} \quad (2)$$

For spheres of uniform size, the specific surface area is given by

$$S_0 = \frac{6}{d_m} \quad (3)$$

where d_m is the diameter of a spherical particle. For mixtures of spheres composed two or more sizes of uniform spheres, the specific surface area of mixture is

$$S_0 = \sum_{i=1}^n X_i S_{0i} \quad (4)$$

where S_{0i} is the specific surface area of different sizes of spheres in aggregate and X_i the volumetric fraction of different sizes of spheres in an aggregate.

For particles departing from spherical shape, d_m in Equation (3) is the diameter of a spherical particle having the same specific surface area as the powder. Accordingly, if K , k , and ε are known, it is possible to calculate the specific surface area of any homogeneous powders by the Equation (2) and (4).

Equation(4) can be applied for mixture of powders composed of n heterogeneous materials, if the volumetric fraction X_i is expressed by

$$X_i = \frac{\frac{\omega_i}{\rho_i}}{\sum_{i=1}^n \frac{\omega_i}{\rho_i}} \quad (5)$$

where ω_i and ρ_i are the weight fraction and the density of each powder, respectively.

The Kozeny-Carman constant : According to Carman,⁽¹⁾ the constant, k , can be written in the term

$$k = k_0 \left(\frac{L_e}{L} \right)^2 \quad (6)$$

where k_0 is the shape factor believed by Carman to lie within the range 2.0 to 3.0 with a probable average value of 2.5. This assumption was based on the known shape factors of pipes possessed of widely differing but nevertheless relatively simple geometrical shapes. The quantity, $(L_e/L)^2$, is the square of the ratio of the actual average effective length of fluid flow in a porous medium, L_e , to the geometrical length of the medium in the direct of macroscopic flow, L . Carman has suggested the $(L_e/L)^2$ has a value of about 2.0 in all unconsolidated porous media. Then from Equation (6), if k_0 is about 2.5, the magnitude of the Kozeny-Carman constant, k , would always about 5.0. Much evidence that is now available certainly suggests that for unoriented particle aggregates in the porosity range of 35 to 70%, k is $5.0 \pm 10\%$. The recent work of Coulson,⁽²⁾ however, strongly indicates that even in the restricted porosity range of 35 to 45%, k is significantly dependent upon both porosity and particle shape. Sullivan and Hertel⁽³⁾ showed clearly that the orientation of particles in an aggregate affects k . For aggregates of glass fibers, k was found to be 3.0 when flow was parallel to the axis of the fibers and 6.0 when flow was perpendicular to the axis. For aggregates of fibers at very large porosities ($\varepsilon > 0.84$) k was stated by Sullivan and Hertel to increase rapidly. It is apparent that the constancy of k at a value of about 5.0 for aggregates of an oriented particle and at very low or

high porocities must also be suspect. Accordingly, it must be considered that the magnitude of the Kozeny-Carman constant is 5.0 only for unoriented particle aggregates in the porosity range 45 to 70%.

Determination of permearbility : If a fluid is percolated through a porous medium of uniform cross sectinal area, A , and thickness, L , the rate of flow, Q , is given by the Equation⁽⁴⁾

$$u = \frac{Q}{A} = K \frac{\Delta P}{\eta L} \quad (7)$$

where u is apparent linear rate of flow in centimeters per second, K permeability constant representing the permeability of the porous medium, Q rate of flow in milliliters per second, A cross-sectinal area in square centimeters, ΔP pressure difference driving the fluid flow through the medium in grams per square centimeter, η viscosity of fluid in poises, and L the thickness of the porous medium. The permeability of the powder will be obtained by the Equation (7). Accordingly, if the magnitude of the Kozeny-Carman constant, k , is always about 5.0, it may be considered that the specific surface area of the powder can be determined by the Equation (2), (4), and (7). But if the Kozeny-Carman constant is a function of shape factor or porosity of aggregate, the specific surface area of the powder must be determined case by case. The last problem also will be discussed experimentally in next paper.

Projected diameter : For particles departing from spherical shape, it is usual to consider the equivalent diameter, d_e , as defined by Heywood.⁽⁵⁾ The equivalent projected diameter is the diameter of the circle having the same area as has the particle; when the particle is placed in its most stable position on a horizontal plane and viewd from above. For the present purpose, the relationships

$$S = \alpha_s d_e^2 \quad (8)$$

and
$$V = \alpha_v d_e^3 \quad (9)$$

are obtained for a irregularly shaped particle which has a projected diameter d_e , a volume V , and a surface area S . The terms α_s and α_v are called surface and volume coefficient, respectively. Let N be the number of particles per unit weight of material and ρ the density of particles. Then,

$$V = \frac{1}{\rho N} = \alpha_v d_e^3 \quad (10)$$

If now S_0 is, as stated previously, the specific surface area per unit volume of particles in aggregate,

$$S_0 = \rho S N = \frac{\alpha_s}{\alpha_v} \frac{d_e^2}{d_e^3} = \frac{\alpha_s}{\alpha_v} \frac{1}{d_e} = \alpha_{sv} \frac{1}{d_e} \quad (11)$$

where α_{sv} is the value of (α_s/α_v) . Then

$$\frac{6}{d_m} = \alpha_{sv} \frac{1}{d_e} \quad (12)$$

$$\text{or } \frac{d_c}{d_m} = \frac{\alpha_{sv}}{6} \quad (13)$$

§ 3. Experimental procedure.

Measurement of specific volume surface area and permeability : The specific surface area of powder was measured by the air permeability method for powders in subsieve range and by the liquid permeability method for powders in sieve range. The essential parts of the apparatus used for fine powders are shown in Fig. 1. The steel permeability tube, *a*, was of uniform and accurately known cross sectional area. To ensure an even bed, the thickness of which could be measured accurately, it was preferable to use a fairly small diameter (actually 1.02cm. in the apparatus used in this experiment). It was connected by a glass joint, *b*, inner tube, *c*, which had several small hole *c'* below. An outer tube *d* had a graduated measuring sidetube *d'* parallel to its length and joining in just below *e* and *f*. They were connected by a glass joint, *g*, and bent tube, *h*, to the correcting vessel, *i*. The tube *j* connects *i* to a vacuum receiver, equipped with pressure regulator and manometer so that a constant and known vacuum could be produced in *i*. For coarse powders, *j* opened to the atmosphere. The difference of liquid levels between the small hole and the vent *k* then gave the driving head of liquid.

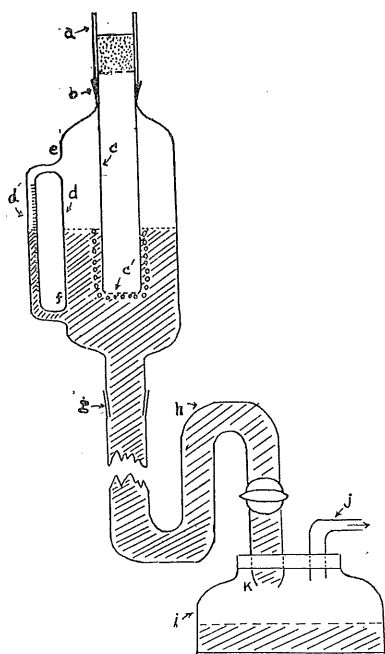


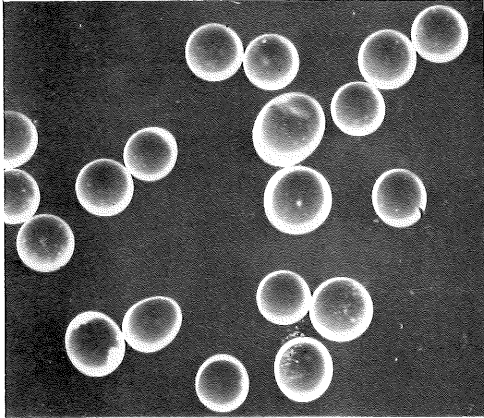
Fig. 1 Permeability Apparatus

The specific volume surface area of sieve range powder was measured by the liquid permeability method.

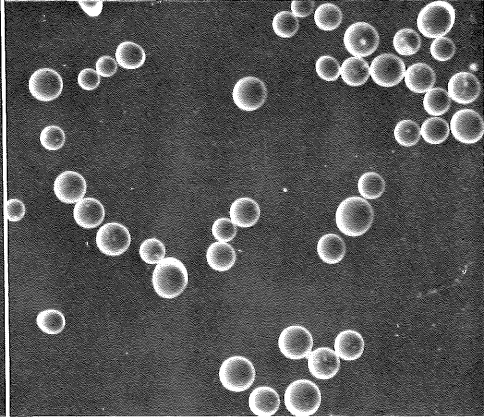
Measurement of projected diameter : The projected diameter was obtained from the projected area of particles in photo-micrographs, using the Amsler's surface meter.

Materials : The physical properties of powders used in this experiment were shown in Table 1, and the photo-micrographs of the powders were shown in Fig. 2, 3, 4, and 5.

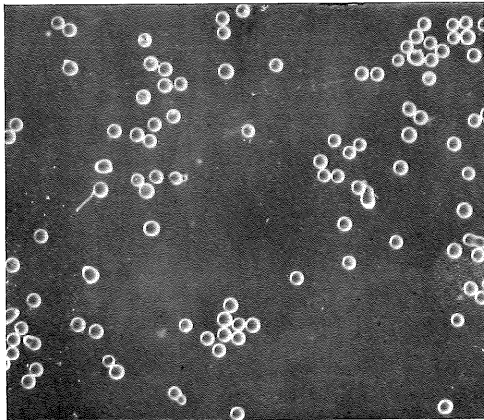
Fig. 2



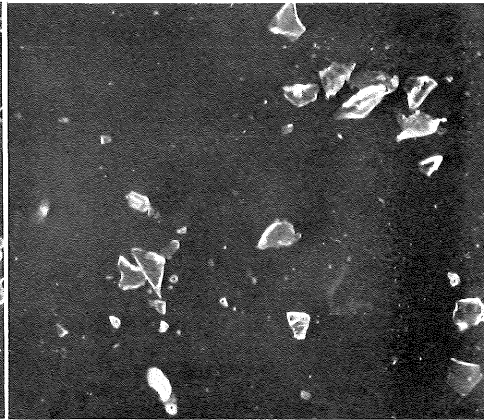
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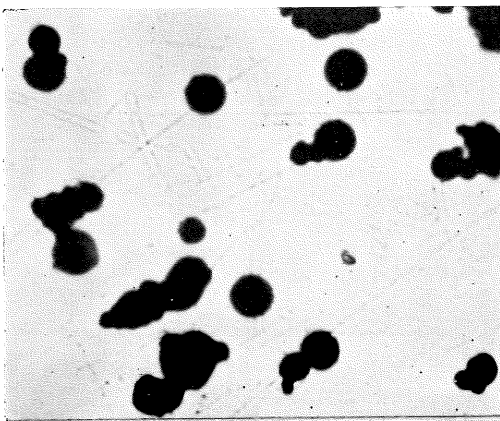
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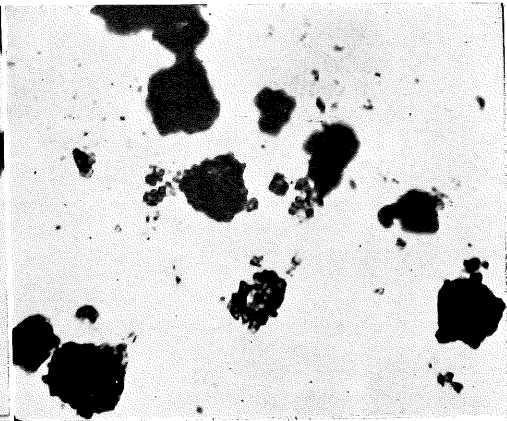
No. 4. Glass. $\times 10$



No. 41. Glass. $\times 13$



No. 60. Zinc $\times 1000$



No. 64. Cuprous Oxide. $\times 500$

Fig. 3



No. 22. Glass. $\times 80$



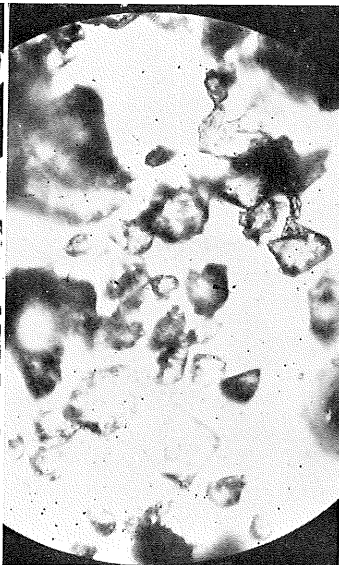
No. 27. Glass. $\times 350$



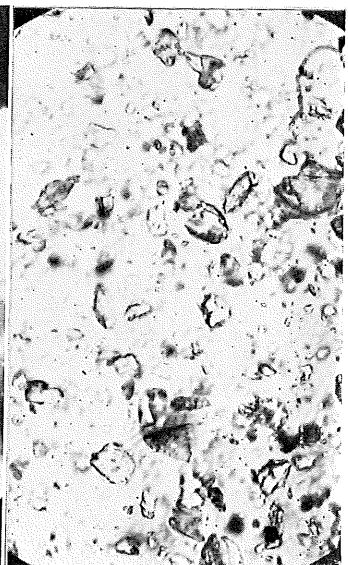
No. 37. Glass. $\times 80$



No. 38. Glass. $\times 80$

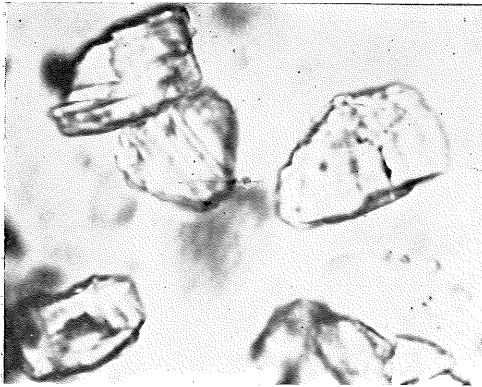


No. 39. Glass. $\times 350$

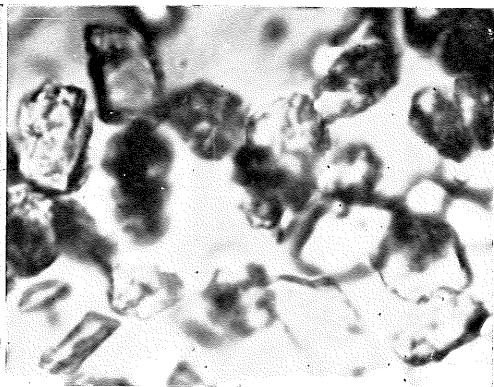


No. 53. Calcium Carbonate. $\times 400$

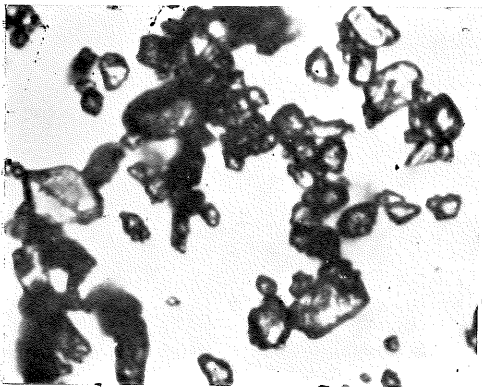
Fig. 4



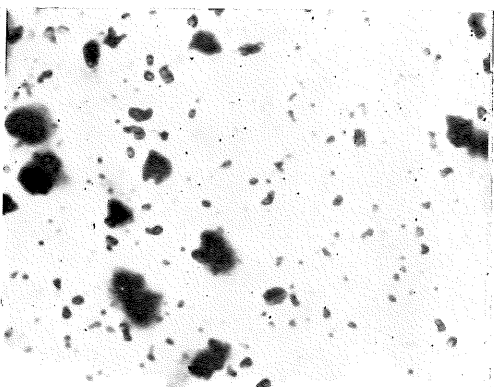
No. 46. Calcium Carbonate. $\times 700$



No. 47. Calcium Carbonate. $\times 700$

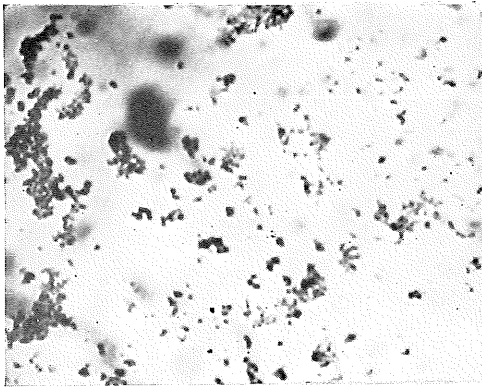


No. 48. Calcium Carbonate. $\times 700$

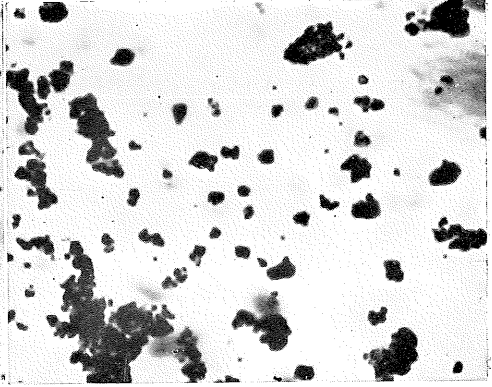


No. 52. Calcium Carbonate. $\times 700$

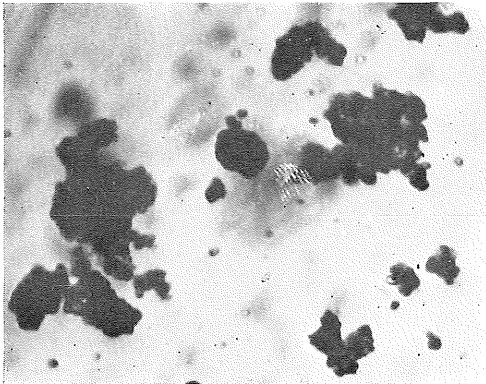
Fig. 5



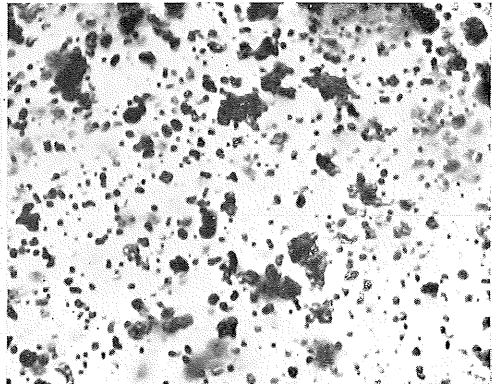
No. 62. Zinc Oxide. $\times 700$



No. 65. Red Oxide. $\times 700$



No. 57. Cupric Oxide. $\times 700$



No. 61. Titanium Dioxide. $\times 700$

The Particle Size of Mixture of Powders

Table 1. Samples.

Sample numbers	Materials	Density g/cc	Makers
No. 1	Glass	2.50	Goto Glass Co.
No. 3	"	"	"
No. 4	"	"	"
No. 22	"	"	Auther's own making
No. 27	"	"	"
No. 37	"	"	"
No. 38	"	"	"
No. 39	"	"	"
No. 41	"	"	"
No. 46	Calcium Carbonate	2.72	Kanto Chem. Co.
No. 47	Calcium Carbonate	"	"
No. 48	"	"	"
No. 52	"	"	Wako Pure Chem. Co.
No. 53	"	"	Kanto Chem. Co.
No. 57	Cupric Oxide	6.32	Koso Chem. Co.
No. 60	Zinc	7.14	Kanto Chem. Co.
No. 61	Titanium Dioxide	4.24	"
No. 62	Zinc Oxide	5.70	"
No. 63	Aluminum Oxide	4.08	"
No. 64	Cuprous Oxide	5.88	"
No. 65	Red Oxide	5.20	"

§ 4. Experimental Results and Discussion.

a) The specific volume surfaces, the diameter of the sphere of equivalent specific surface, the projected diameters, and the surface volume coefficient were measured. The results obtained were recorded in Table 2. In these measurements, the porosity of powder bed lay within the range 45 to 70%. Accordingly, the Kozeny-Carman constant 5.0 was taken for the calculation of permeability. From these results, we understood the following facts : 1) On the sphere Glass, the surface diameter was equal approximately the projected diameter. On the irregular Glass, the difference between them was large, but the size of the surface diameter corresponded with the size of the projected diameter. 2) On the other powders, the difference between them was more large. It seems that the projected diameter of fine powders had a large experimental error. Especially, the measurement of the projected diameter was very difficult, when the difference of powders composed was extremely large as the samples No. 64, and No. 57. 3) The calculated value of the surface volume coefficient for a ideal uniform sphere is 6.04. In our experimental result, the mean value of the surface volume coefficient for sphere glass was 6.70. For the irregular particle, the surface volume coefficient was smaller than it for the spherical particle. In our experiment, also, it was satisfied except No. 57, 52, 48, and 64 which had the large difference of size composed of.

Table 2. Sizes of Samples

Sample numbers	Specific surface, cm ² /cc	Surface diameter, cm	Projected diameter, cm	Surface-volume coefficient
No. 1	7.04·10	9.62·10 ⁻²	1.11·10 ⁻¹	7.81
No. 3	1.11·10 ²	5.41·10 ⁻²	4.43·10 ⁻²	7.14
No. 4	2.74·10 ²	2.19·10 ⁻²	1.88·10 ⁻²	5.15
No. 22	1.25·10 ³	4.80·10 ⁻³	2.81·10 ⁻³	3.51
No. 27	6.25·10 ³	9.60·10 ⁻⁴	2.36·10 ⁻⁴	1.46
No. 37	1.50·10 ³	4.00·10 ⁻³	1.68·10 ⁻³	2.52
No. 38	1.97·10 ³	3.10·10 ⁻³	2.42·10 ⁻³	2.10
No. 39	4.42·10 ³	1.36·10 ⁻³	1.33·10 ⁻³	1.70
No. 41	5.77·10 ²	1.04·10 ⁻²	5.21·10 ⁻³	3.01
No. 46	4.84·10 ³	1.24·10 ⁻³	3.04·10 ⁻³	1.47
No. 47	7.15·10 ³	8.40·10 ⁻⁴	3.23·10 ⁻⁴	2.31
No. 48	1.88·10 ⁴	3.20·10 ⁻⁴	7.68·10 ⁻⁴	14.4
No. 52	2.61·10 ⁴	2.30·10 ⁻⁴	5.25·10 ⁻⁴	13.7
No. 53	2.73·10 ⁴	2.20·10 ⁻⁴	1.94·10 ⁻⁴	5.30
No. 57	7.90·10 ⁴	7.60·10 ⁻⁵	2.11·10 ⁻⁴	16.7
No. 60	7.92·10 ³	7.55·10 ⁻⁴	1.02·10 ⁻⁴	0.808
No. 61	7.11·10 ⁴	8.44·10 ⁻⁵	—	—
No. 62	7.84·10 ⁴	7.65·10 ⁻⁵	—	—
No. 63	1.82·10 ⁴	3.30·10 ⁻⁴	—	—
No. 64	2.03·10 ⁴	2.95·10 ⁻⁴	3.48·10 ⁻⁴	7.08
No. 65	1.05·10 ⁵	5.70·10 ⁻⁵	—	—

b) The correlation between the specific surface area of mixtures and their volumetric fraction on the homogeneous powder of having different sizes were shown in Fig. 6, 7, and 8, and the surface equivalent diameter, projected effective diameter, and surface volume

Fig. 6 Correlation between the specific volume surface and volumetric fraction of glass sphere.

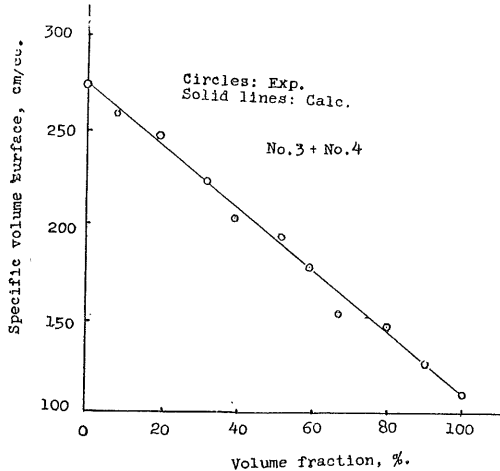
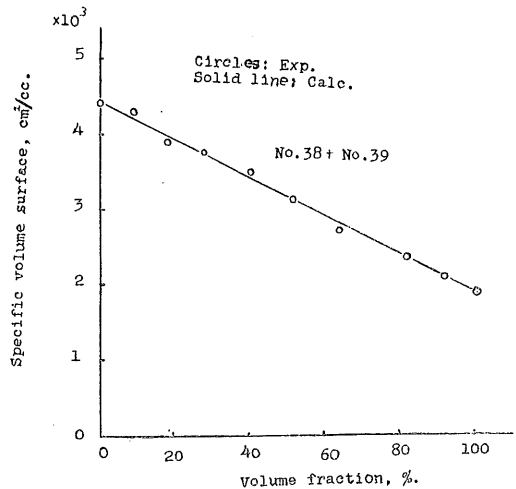


Fig. 7 Correlation between the specific volume surface and volumetric fraction of irregular shaped glass powder.



The Particle Size of Mixture of Powders

Fig. 8 Correlation between the specific volume surface and volumetric fraction of Calcium Carbonate.

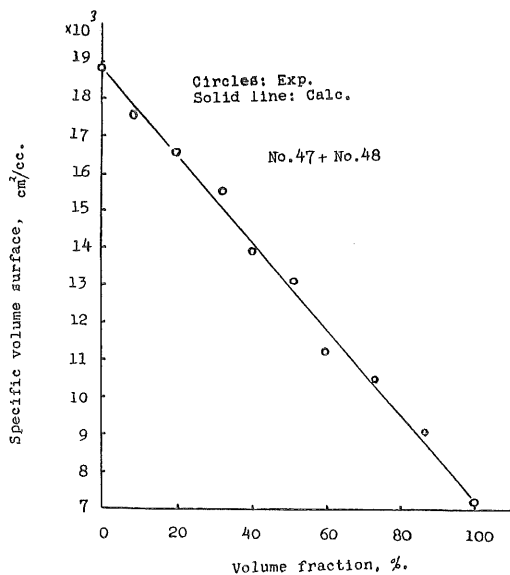


Table 3. The particle sizes of mixtures of Glass powder.

Composed sample numbers	Volumetric fraction %	Specific surface cm²/cc	Surface diameter cm	Projected diameter cm	Surface-Vol. coefficient
No. 1	16.7	Exp. 191	$3.14 \cdot 10^{-2}$	$2.85 \cdot 10^{-2}$	5.45
No. 3	33.3	Calc. 186	$3.23 \cdot 10^{-2}$		
No. 4	50.0				
No. 1	16.7	Exp. 160	$3.75 \cdot 10^{-2}$	$3.10 \cdot 10^{-2}$	4.96
No. 3	50.0	Calc. 159	$3.79 \cdot 10^{-2}$		
No. 4	33.3				
No. 1	50.0	Exp. 114	$5.26 \cdot 10^{-2}$	$5.30 \cdot 10^{-2}$	6.05
No. 3	34.0	Calc. 117	$5.08 \cdot 10^{-2}$		
No. 4	16.0				
No. 1	33.3	Exp. 187	$3.21 \cdot 10^{-2}$	$2.90 \cdot 10^{-2}$	5.42
No. 3	16.7	Calc. 179	$3.45 \cdot 10^{-2}$		
No. 4	50.0				
No. 41	10.1	Exp. 1952 Calc. 1614	$3.77 \cdot 10^{-3}$ $3.82 \cdot 10^{-3}$	$3.01 \cdot 10^{-2}$	4.79
No. 22	19.3				
No. 47	30.1				
No. 38	21.5				
No. 39	8.3				
No. 27	11.7				

coefficient were recorded in Table 3. From the results in Table 3, Fig. 6 and 7, we understood the following facts : 1) The specific surface area of mixture of homogeneous spherical powder, if the volumetric fraction and the specific surface of composed powder was known, could be calculated by Eq.(4). The calculated value was good agreed with the experimental it as shown in Table 3 and Fig. 6. 2) For the irregular particle, if the each composed powder was the same kind, also the specific surface of mixture could be calculated by Eq. (4) as shown in Table 3, Fig. 7, and 8. Since the mean value of surface volume coefficient was 5.33 our results satisfied the Eq. (4) for the mixture of homogeneous powder in sieve range.

c) The correlation between the specific volume surface area of mixtures and their volumetric fraction on the heterogeneous powders of having different sizes were shown in Fig. 9, and the surface equivalent diameter, projected effective diameter, and surface volume coefficient were recorded with values calculated by Eq. (4), (5), and (11) in Table 4. From these results, we understood the following facts : 1) The specific surface of mixtures of heterogeneous powder could be calculated by Eq. (4) and (5). The agreement of calculated value with our experimental value was good for mixture of two powders. 2) On the other hand, if the kind of composed powders was increased, the agreement was bad. But these results was satisfactory for our purpose.

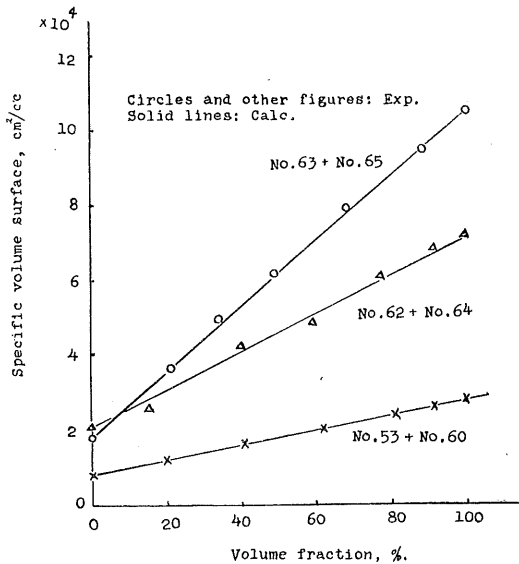


Fig. 9 Correlation between the specific volume surface and volumetric fraction of heterogeneous powders.

Table 4. The particle sizes of mixtures heterogeneous powders.

Composed sample numbers	Density, g/cc	Weight fraction, %	Specific surface, cm²/cc × 10⁴	Surface diameter, cm × 10⁻⁴
No. 62	4.753	50	Exp. 5.45	1.10
No. 63		50	Calc. 5.31	1.25

The Particle Size of Mixture of Powders

Composed sample numbers	Density, g/cc	Weight fraction, %	Specific surface, cm ² /cc × 10 ⁴	Surface diameter, cm × 10 ⁻⁴
No. 61	4.861	50	Exp. 7.44	0.807
No. 62		50	Calc. 7.55	0.795
No. 53	3.944	50	Exp. 1.33	4.51
No. 60		50	Calc. 1.31	4.52
No. 65	4.682	50	Exp. 9.54	0.623
No. 61		50	Calc. 9.11	0.658
No. 63	3.718	33.3	Exp. 6.59	0.90
No. 53		33.3		
No. 61		33.3	Calc. 4.31	1.39
No. 60	4.027	33.3	Exp. 4.31	1.39
No. 53		33.3		
No. 61		33.3	Calc. 3.75	1.60
No. 60	5.310	25	Exp. 6.79	0.884
No. 65		25		
No. 63		25	Calc. 5.26	1.14
No. 62		25		

§ 5. Conclusion.

The specific volume surface area of mixtures of powders were experimentally considered. If the porosity of aggregate lay within the range 45 to 70%, the specific volume surface of mixtures was calculated from the specific volume surface and the volumetric fraction of composed powders. The agreement of the calculated value with the experimental value was good for the spherical or homogeneous powders. For the heterogeneous powder, the agreement became bad as the kind of composed powders was increased. But these results were satisfactory for our purpose. Also, it was understood that the surface volume coefficient was the simple factor which expressed the size of powders. When the shape factor is the function of porosity, these problem will be more difficult.

§ 6. Acknowledgement.

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Kiyoshi Shimizu

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